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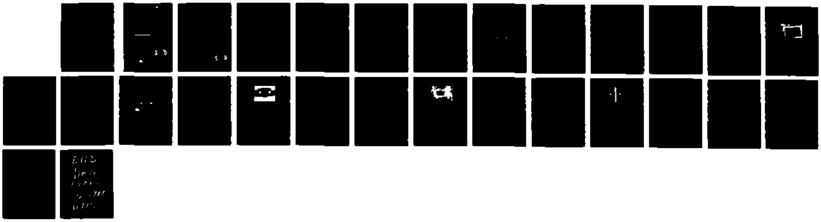

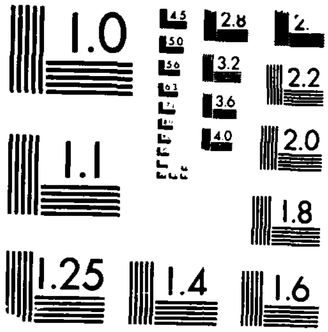

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ATTACHABLE INTERFEROMETRIC STRAIN GAGES

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February 1988

ATTACHABLE
INTERFEROMETRIC
STRAIN GAGES

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Laser-based interferometry from tiny reflective indentations can be used to measure in-plane strain/displacement over a very short gage length (on the order of 100 μm). If the specimen material is not reflective, then some other means of generating the interference patterns must be found. This report describes two kinds of attachable gages: plated acetate replicas of indentations and relective foils that are indented after application. In either case, the gage is applied with the techniques used for foil resistance gages and the gage itself is very small. The manufacturing procedures are described.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) and the results of experiments comparing the strain to that measured with foil resistance gages are presented.

A third type of interferometric gage with a long gage length, 25 mm, is also described and evaluated.

INDEX

INTRODUCTION

The Interferometric Strain/Displacement Gage (ISDG) is a laser-based technique for measuring the relative displacement between two reflecting surfaces on a specimen. These reflecting surfaces are impressed into the surface of a specimen with a Vickers microhardness tester and are very small and close together. When they are illuminated with a laser, interference patterns form in space; motion of these fringe patterns is related to the change in distance between the indentations. The small size of the "gage" (a gage length on the order of 50 micrometers) is one of the most attractive features of this technique in experimental solid mechanics.

The ISDG has been used for a variety of applications over the years, and these are summarized in a review article [1]. Examples of applications are cyclic plastic strain measurements at 650C on nickel-based superalloy specimens [2] and crack opening displacement measurements across very small fatigue cracks [3]. In applications to-date there have been no reasons to suspect that the presence of the indentations had a damaging effect on the response of the specimen. However, there are applications where it would be preferable to have a set of indentations in a "gage" that could be attached to the specimen or component and then interrogated with a laser-based measurement system. One example is measurements in high temperature or corrosive environments where the gage material could be made from a non-oxidizing material. Another application would on nonreflective materials such as plastics or composites.

This is a report on the development of three kinds of attachable gages for use with the ISDG system. A brief explanation of the ISDG is given next; followed by an evaluation of the response of direct indentations. The first attachable gage is an acetate replica of indentations that is sputtered to make it reflective. The second gage consists of a thin foil that is glued to the specimen and then indented. The third gage has a gage length of 25mm and consists of two strips glued onto the specimen with indents across their ends. All three kinds of gages were evaluated by comparing their response with a foil resistance strain gage mounted on the same specimen. The capabilities of the acetate gage were demonstrated by measuring "strain" across a grain boundary. Finally, just for fun, indentations were placed in the foil of a resistance strain gage to measure strain on a strain gage. The details of the three approaches and the results of the evaluations are presented in some detail.

BASICS OF THE ISDG

Figure 1 is a photomicrograph of a pair of indentations impressed directly into the specimen surface with a Vickers microhardness tester. The indents are 100 micrometers apart and are each approximately 12 micrometers square and 3 micrometers deep.

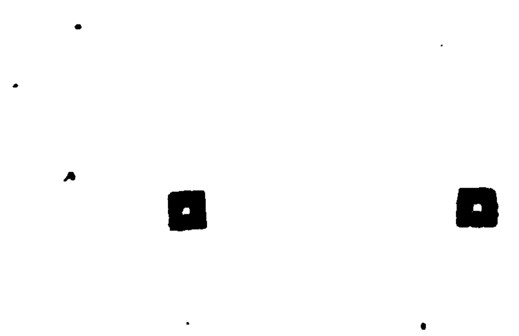

Figure 1: A pair of indentations; they are 100 micrometers apart.

When an indentation is illuminated with a laser beam perpendicular to the specimen surface, light is diffracted from each of the four triangular-shaped sides. Since the indents are so close together, the diffracted light rays overlap and interfere to form fringe patterns in space. The position of fringes of a given order in the patterns above and below the set of indents (as viewed in Figure 1) is proportional to the distance between the indents. This is simply the two-slit interference phenomenon of Young [4] except that it is in reflection, not transmission. The other two fringe patterns on either side of the indentations are not used in these measurements.

It is the relative change in the distance between the indents that is of interest here, and that change causes motion of the fringes. The interference fringes move within the diffraction pattern emanating from the individual indents. More details of the optical principles are given in [1]. The relation between the fringe motion and the relative displacement is given by:

$$\delta d = \frac{\delta M_1 + \delta M_2}{2} \frac{\lambda}{\sin \alpha_0}$$

where λ is the wavelength of the laser, α_0 is the angle between the incident laser beam and the fringe patterns, and δM_1, δM_2 are the relative fringe motions. "Relative fringe motion" means the displacement of a fringe divided by the distance between it and the next fringe. It is necessary to average the two relative fringes shifts to eliminate the effects of rigid body motion in the vertical (in Figure 1) direction.

The wavelength of a He-Ne laser is 0.6328 micrometers, and α_0 is typically 42 degrees. The quantity $\lambda/\sin\alpha_0$ is then 0.94 micrometers; this means that an average relative fringe motion of 1 corresponds to a relative displacement of that amount. If the gage length is 100 micrometers, then the strain resolution is 1 percent. There are many applications where a resolution on that order is quite satisfactory, but it is really too coarse for typical strain measurement.

It is therefore necessary to use some procedure for measuring finer increments of fringe motion. A minicomputer-based fringe scanning system [5] has been developed that is capable of dividing the fringe spacing into 100 parts. For static or slow cyclic testing, the minicomputer-based system in current use at Hopkins has a resolution of 0.01 micrometers and takes data at the rate of 10 data points per second. One can also use the ISDG for dynamic measurements with photomultiplier tubes and an oscilloscope to record the rapid fringe motion. In this case, the resolution is approximately 1/2 micrometer. In either situation, the short gage length of the ISDG offers an advantage that, in certain situations, permits measurements that were previously impossible.

DIRECT INDENTATION GAGE

As mentioned above, the previous applications of the ISDG have used indentations directly into the specimen surface. The strain response of direct indentations was measured to serve as a baseline for comparison of the attachable gages and is described in this section. Notice in Figure 1 that the specimen surface is not polished especially well. A surface sanded with 600 grit paper is satisfactory provided the final scratches run parallel to the line between the indentations; the reflections from the scratches then do not overlap the fringes.

The specimen was made of 2024 aluminum and was 50mm wide by 2.3 mm thick with a test section 100 mm long (the dimensions were chosen to fit existing test machine grips). A MicroMeasurements type EA-13-062UW-120 foil resistance strain gage (RSG) was applied on one side of the specimen, and direct indentations were placed on the edge (again, to conform to an existing test machine setup). The foil strain gage was recorded manually from a Vishay P3500 strain indicator. The indentations were illuminated with a 15 milliwatt He-Ne laser, and fringe motion was monitored with the minicomputer-controlled ISDG system. So, it was possible to measure strain simultaneously with the ISDG and a RSG on a uniformly strained specimen.

The results of this comparative experiment are presented in Figure 2. The specimen material is seen to be very ductile - a desirable feature in this case because it enables comparison of the two techniques for strains up to almost 1 percent. The circles in that figure are the RSG data and the points are the ISDG data. One observes that the ISDG data are distributed along discrete vertical lines - especially in the elastic region. This is caused by the discrete nature of the computer-controlled measurement system. It divides the distance between fringes into approximately 90 discrete parts corresponding to a displacement increment of slightly more than 0.01 micrometer. If one counts the increments in Figure 2 for the strain to 0.0025, one counts 23 increments. The electrical and optical noise make it difficult to improve the resolution unless the data sampling is slowed considerably. Of course, the RSG data could have been recorded continuously with a resolution on the order of 1 microstrain (compared to 100 microstrain for the ISDG) and presented as a smooth line.

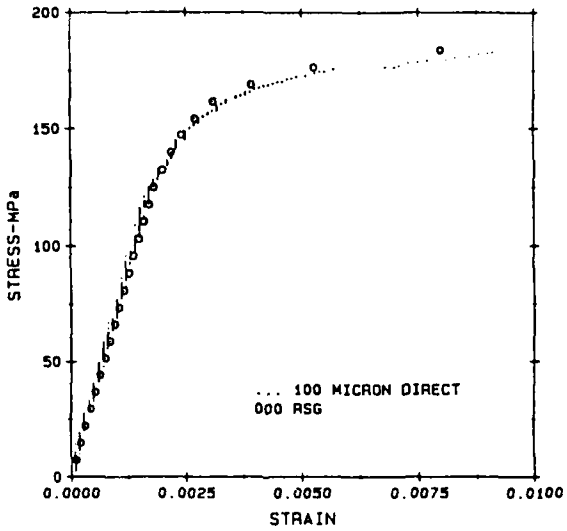

Figure 2: ISDG strain and RSG strain compared.

The agreement of the ISDG with the RSG is excellent until well into the plastic strain region where the ISDG shows a somewhat larger strain. The foil gage fell off in this test, and it possibly was not recording properly just before the maximum recorded strain was reached. This agreement is not at all surprising; previous work with the ISDG support it. But, the results in Figure 2 serve as a baseline for the evaluations of the two new techniques described below.

ACETATE GAGE

The acetate gage is constructed by taking a replica of a set of indentations, turning it over, plating it for reflectivity, and gluing it to the specimen. Acetate replicas are frequently used in microscopy to examine surface details; the replicas serve as a permanent record of the state of the surface at a particular stage and can, by viewing in a scanning electron microscope, enable very high magnification of portions of a large specimen. One interesting application was in the measurement of the growth of very short fatigue cracks [3] Replicas were taken at regular intervals until a crack had grown long enough to be easily detectable. One then looked back through the replicas at cracks that were too short to be detected earlier without exceptional care; this permitted one to establish a growth pattern from the very beginning for cracks less than 35 micrometers long.

The replica material was acetylcellulose from Bioden R.F.A. and was 34 micrometers thick. This is a special, high quality material, but successful replicas have been taken with the acetate material used for overhead transparencies. A "master" set of indentations was impressed into a highly polished block of IN 718 (the kind of material is unimportant) with the Vickers microhardness tester. One drop of acetone is placed over the indents and then a piece of the replica material approximately 15 x 50 mm is pressed down over them and held with thumb pressure for a minute. The acetone dissolves the acetate into the indentations and produces a replica of very high fidelity.

After the replica is removed from the master, it is necessary to dry it although that is not normally done for microscopy. The replica is placed on a glass microscope slide and held flat with a special jig that has an opening for the replicas of the indents (which are pyramids sticking up out of the surface). The fixture is placed in an oven for 50 minutes at 90C. Next, a thin layer of gold is sputtered onto the replica in a small sputterer used normally for coating SEM specimens. A current of 10 milliamps for 5 minutes is satisfactory and produces a coating approximately 1-2 micrometers thick that is highly reflective even though it is still translucent. The initial drying operation is necessary to prevent severe curling of the replica during the coating process.

One now has a coated replica of two indents that are perhaps only 50 micrometers apart, and the next step is to cut them out of the larger piece to make a gage. It is fairly easy to cut out a strip of the coated replica a few hundred micrometers wide and 50 mm long that contains the indents. This strip can then be easily handled for positioning the indents on the specimen. If a smaller gage is desired, it too can be cut from the larger coated replica. Gages on the order of 150 micrometers square have been cut using a scalpel attached to a three-axis micromanipulator with the aid of a stereo microscope.

Handling such small gages is a bit of a problem, but cellophane tape is used to pick them up and locate them on the specimen. They are then attached to the specimen using exactly the same techniques as for foil resistance strain gages.

Again, a stereo microscope is useful if one must locate the indentations precisely. Figure 3 is a photomicrograph of an acetate gage adhered to a surface. The indents are 100 micrometers apart, so the gage is roughly 150 x 300 micrometers. One can see the adhesive (M-Bond 200 by MicroMeasurements) around the edges of the gage.

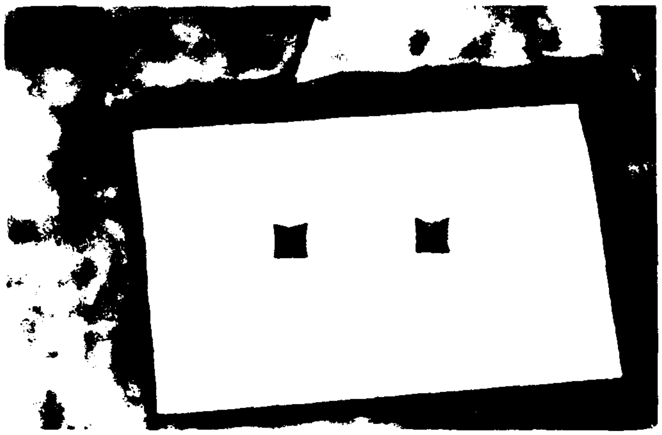

Figure 3: An acetate ISDG; the pyramids are 100 micrometers apart.

Figure 4 is a plot of the results of an evaluative test conducted in the same fashion as the direct indentation test described in the previous section. That is, the acetate gage was on the edge of the specimen, and the resistance gage was on the side. Again, excellent agreement is obtained well into the plastic region.

The gage of Figure 4 had a gage length of 100 micrometers, but Figure 5 shows the results of another test of an acetate gage with a gage length of only 25 micrometers. The indent replicas were approximately 7 micrometers square. The dots in Figure 5a denoting the ISDG data show the effect of the reduced strain resolution because of the shorter gage length. The resolution has been reduced by a factor of four compared to Figures 2 or 4 and is now approximately 400 microstrain. The noise is also more pronounced. But if one post-processes the data by averaging the stress values at the discrete strain values, one gets the smoother results of Figure 5b. These strain readings are somewhat remarkable - accurate measurements over a gage length of 25 micrometers. The shortest commercially available foil resistance

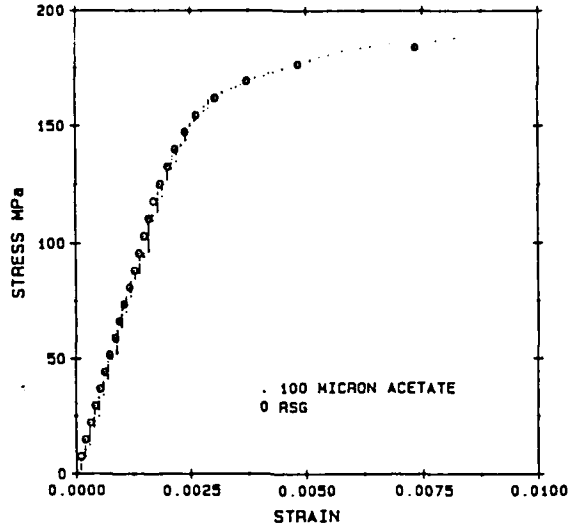

Figure 4: Strain measured with the acetate ISDG compared with an RSG.

gage has a gage length of 200 micrometers, but the total size of the gage including the tabs is much larger; however, the resolution is considerably better.

FOIL GAGE

A simpler version is the foil gage where a foil is glued to the specimen and indentations applied with the reflective material in place. The foil is soft aluminum that is 8.9 micrometers (0.00035 inches) thick; thinner or thicker foils, and of course other materials, are available. A small rectangular piece of foil is cut by placing the foil on a glass microscope slide and pressing straight down with a new razor blade. This is done without the aid of a stereo microscope because one can select the best gage blank from a number of candidates. The gage blank, which is on the order of hundreds of micrometers long, is then picked up and handled with cellophane tape and finally applied with M-Bond 200 adhesive.

After the foil gage blank is attached to the specimen, the indentations are impressed with the Vickers microhardness tester. One can locate the indents very precisely with reference to other features on the specimen that are not obscured by the foil. Since the indentations are only five or so micrometers deep, they do not

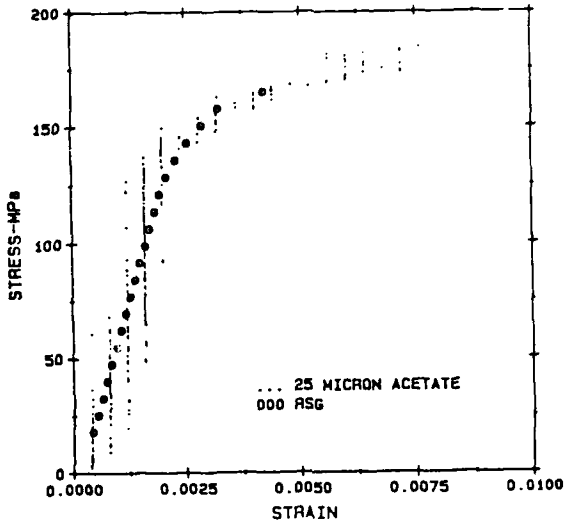

Figure 5a

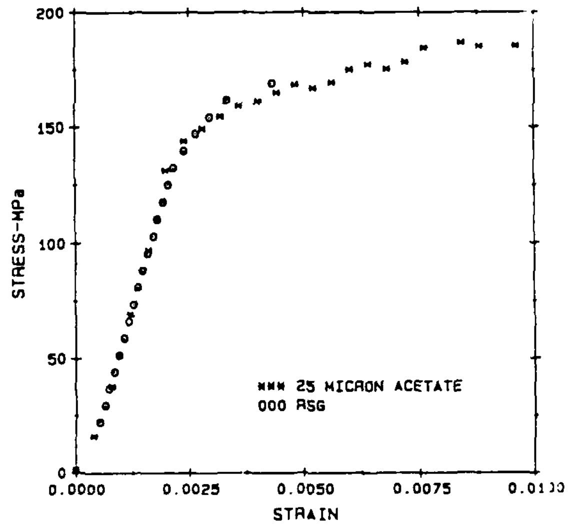

Figure 5b

Figure 5: Strain measured with an acetate ISDG with a gage length of 25 micrometers. Figure 5a is the raw data, and Figure 5b is averaged data.

penetrate the foil blank, yet they are very near the specimen surface. Figure 6 is a photomicrograph of a foil gage. It is approximately 1.5 x 1.8 millimeters square (there was no need for it to be smaller in this application), and the gage length is 100 micrometers. Note how rough the foil surface is because it has been pressed onto an unpolished surface. This does not prevent successful indentations. Note also that the rolling marks on the foil are parallel to the gage direction.

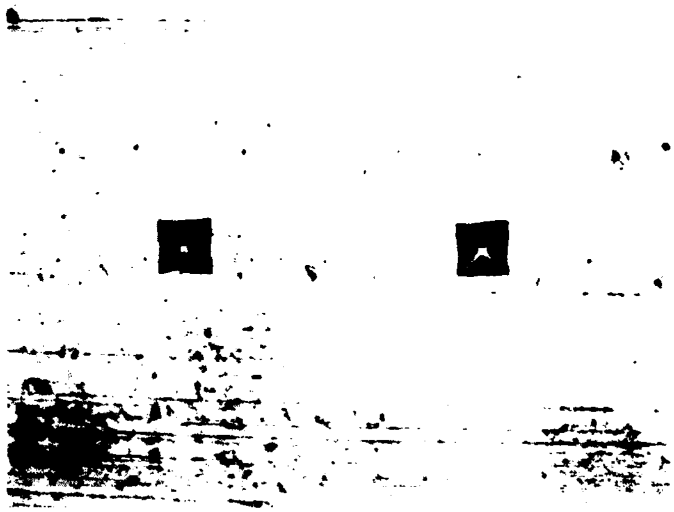

Figure 6: A foil ISDG; the indentations are 100 micrometers apart.

Figure 7 is another plot comparing the output of the ISDG with a foil resistance gage. It too shows excellent agreement between the two measurement techniques. Some of the resistance gage data is missing in the plastic region because the strain was changing too fast to be recorded manually. This foil version of the ISDG offers considerable advantages. It uses the proven technology of foil resistance gages for attachment, reduces the amount of specimen surface preparation, offers the possibility of non-oxidizing reflective surfaces, and, last but not least, removes the need to indent the surface of the specimen.

STRAIN ON A RESISTANCE STRAIN GAGE

Out of curiosity, the ISDG was used to measure the strain in one of the strips

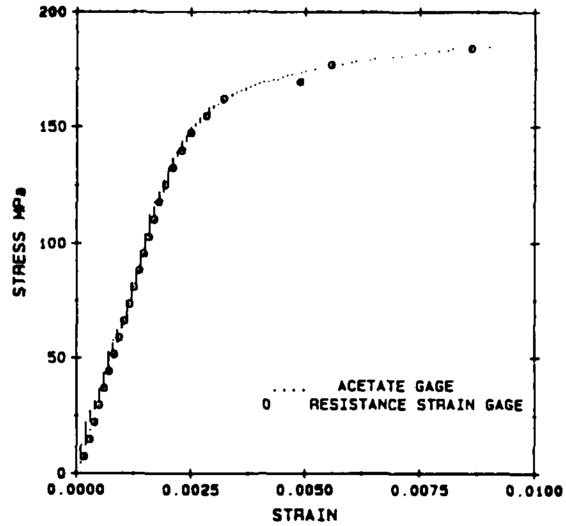

Figure 7: Foil ISDG strain compared with RSG strain.

in a foil resistance strain gage grid. Figure 8 shows an acetate and a direct ISDG applied to a MicroMeasurements type EA-13-500AF-120 gage. The resistive strip is 200 micrometers wide, and the gage length is 200 micrometers for increased resolution. Note that the sides of the indents in Figure 8b are convex instead of straight; this is because the thin resistive foil strip sits on a polymeric carrier that deforms when the indents are applied. Nevertheless, those indents worked fine.

Figure 9 compares the strain measured by the direct indent ISDG with that measured by the gage itself. The plot could be made prettier by averaging the data as in Figure 5b, but it is easy to see that the agreement is again very good over a total strain of 1500 microstrain. Note the improvement in resolution with the longer gage length. In practice, one can extend the gage length to around 500 micrometers without changing the general operation of the ISDG system. The fringes become more closely spaced which requires a very narrow aperture for the detector and reduces the optical signal. There have been applications of the ISDG with a gage length of 10 millimeters.

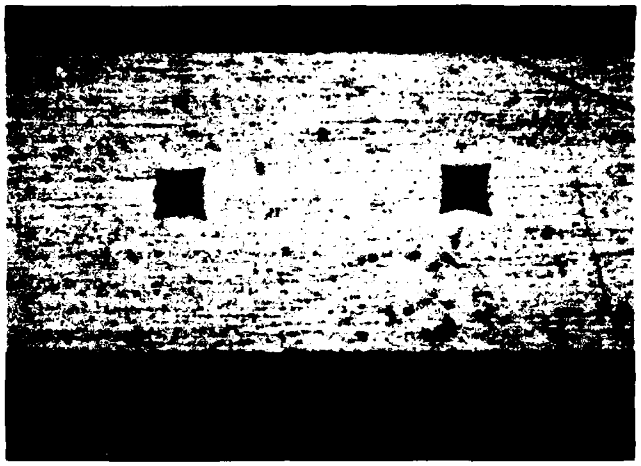

Figure 8: A direct ISDG on one strip of a large foil resistance strain gage. The direct indentations are 200 micrometers apart.

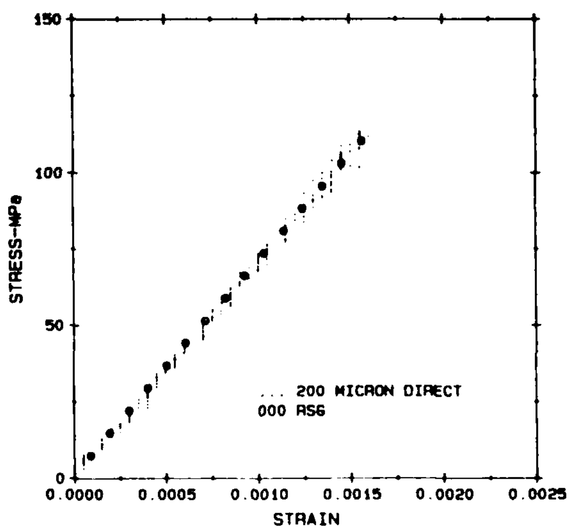

Figure 9: Comparison of the direct ISDG strain measured on a foil RSG with the strain measured by the RSG.

EFFECT OF HEIGHT/LENGTH RATIO

With such a small gage, it becomes necessary to examine the effect of the height of the gage relative to its length. The acetate gage is 34 micrometers high, and the entire gage may be only 200 or 300 micrometers long.

Figure 10 is a plot of the percent error generated by measuring strain between two points on the top of a gage. The calculations were done with a two-dimensional finite element code, and the gage was modeled as a rectangular cross-section with length 2L, height H and an elastic modulus of 1380 MPa (corresponding approximately to the acetate). A uniform displacement was imposed on the bottom of the rectangle to simulate a uniform strain field. The true displacement is imposed on the bottom of the rectangle at a position X on either side of the center line of symmetry. The "measured" displacement is taken at the corresponding X position on the top of the gage. Strains are calculated as these displacements divided by the length X.

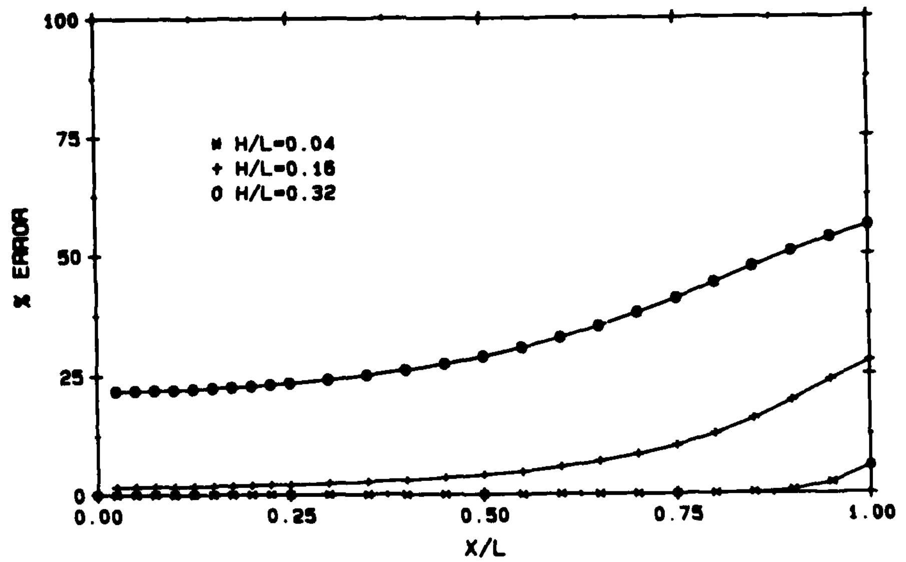

Figure 10: Percent error generated by measuring above the specimen surface at various indentation locations.

The H/L ratio of 0.16 corresponds to the acetate gage described herein with a total size of the gage being 200 micrometers. A small error is always present, but it begins to increase when the indentations are located more than 100 micrometers from the centerline (a gage length of 200 micrometers). So, for a gage with this H/L ratio, one should not make the gage length more than half the total gage size. There is virtually no problem with location of the indents for a very small H/L ratio, and large ratios are intolerable. Another way of looking at these calculations is that they predict the influence of end effects on the gages. The calculations do show that one should not expect significant errors from the attachable gages described here. The foil gage is very thin, and although the computations were done using the elastic modulus for the acetate, one would expect little error from the geometry of the foil gages.

MEASUREMENT ACROSS A GRAIN BOUNDARY

Given its short gage length and generally small size, the ISDG holds potential for use in micromechanics. There are other techniques, such as Moire interferometry and scanning electron microscopy, which enable one to make measurements on a scale consistent with the microstructural features of the material. However, there is some advantage to a technique that produces a realtime measurement at a precisely located position on a specimen. The potential of the ISDG for studies of this nature was demonstrated by measuring the relative displacement across a grain boundary in a copper specimen.

The copper specimen was strain-annealed to grow reasonably large grains. No additional straining was done; the specimen was simply annealed at 1200F for 2 hours and then allowed to cool in the furnace. It was etched with nitric acid to reveal the grain boundaries. There were portions of the specimen where the grains were approximately 0.3 mm in size ; larger grains could be grown by refinement of the strain anneal process.

An acetate gage with the reflecting pyramids 60 micrometers apart was glued across the grain boundary as shown in Figure 11. The photomicrograph shows the grain boundaries, but not the one under the gage. However, the grain boundary under the gage can actually be seen through the translucent acetate ISDG. A sketch is included in Figure 26 to show the position of the gage relative to the boundary.

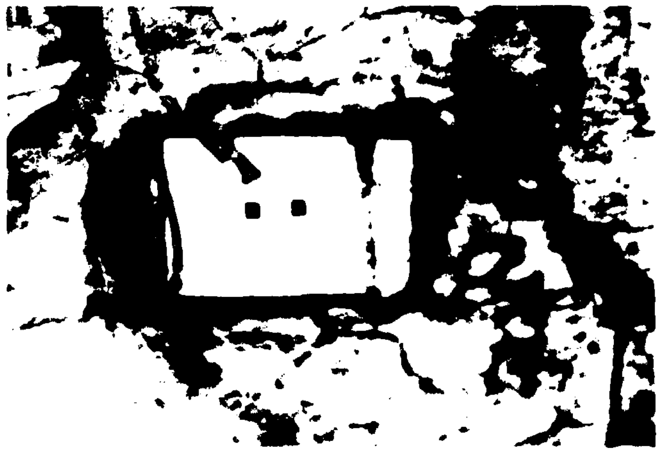

Figure 11: An acetate ISDG placed across a grain boundary; the distance between indentations is 60 micrometers.

The specimen was then loaded in the test machine and the "strain" versus gross stress recorded as shown in Figure 12. Note that the data points are averages of the ISDG measurements. One sees a smooth nonlinear response although its meaning is not clear because the relative orientation of the grains are not known. In fact, the gage is really too large in relation to the grains to be useful here. But the point of the exercise was to demonstrate that one could make and position a gage that could make measurements over such a small scale.

A LONG ISDG

While the short gage length is a primary advantage of the ISDG, there are situations where it is a distinct disadvantage. If the microstructure of a material is large and one wants to measure global properties such as the elastic modulus, one needs a large gage length. Such measurements are easily made at moderate temperatures on large specimens, but they are difficult, if not impossible, at higher temperatures — above 700C, say. The long ISDG which is described in this section was developed with an eye toward eventual application at high temperatures for the measurement

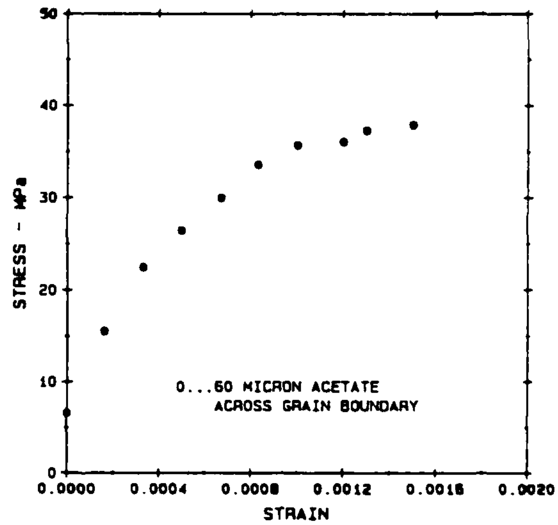

Figure 12: "Strain" measured across a grain boundary.

of mechanical properties of newer materials such as graphite composites. Note that the ISDG, with its inherent stability, has potential for determination of creep behavior also.

The idea behind the long ISDG is shown schematically in Figure 13. The gage itself consists of two separate strips that are bonded to the specimen at one end and butted against each other at the other. Indentations are placed across the joint between the strips to measure the relative displacement between them. This is an approach used in many types of extensometers; spacers are used to transmit the relative displacement to a sensitive device such as a capacitance probe for example. The resolution potentially attainable with a long ISDG is attractive; 0.01 micrometer over a 25,000 micrometer gage length for a strain resolution of 0.04 microstrain.

A room temperature version was developed along the lines of Figure 13. Small pieces of aluminum foil were used at each end of the gage to raise it slightly above the specimen surface. It would be possible to place the brass strips directly on the surface, but it would be hard to define the gage points precisely. Even though the brass strips are only 75 micrometer (0.003 inch) above the specimen surface, it was found necessary to insert a thin piece of Teflon under the middle of the gage

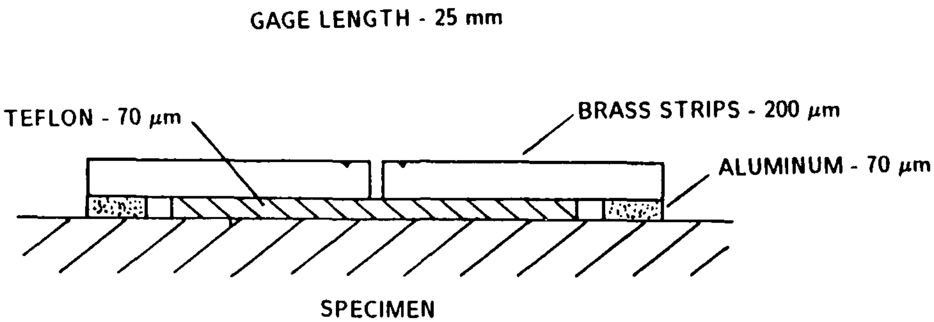

Figure 13: Schematic of a long ISDG.

to prevent the strips from bending. In fact, the most difficult part of the whole assembly is keeping the brass strips straight and in line during the construction of the gage. An ideal strip material would be very stiff, but still soft enough to allow indentation. The indents are applied after the brass strips has been glued to the specimen.

An unexpected and major problem in the gage development came from the reflections from the joint between the two strips. These reflections went right into the fringe patterns. The solution was to lightly sand (with 600 grit paper) the gage after it had been applied. This produced a very sharp vertical edge at the end of each strip and minimized the reflections from a more rounded edge. A set of indents is shown in Figure 14; note that the sanding scratches run parallel to the gage to reflect the laser beam away from the useful patterns.

evaluation of the long ISDG did not use the computer-controlled high resolution system because acceptable resolution can be attained with much instrumentation. One needs only to record the fringes as they pass a fixed position to achieve a reasonable sensitivity. A plot of the fringe intensity versus load is given in Figure 15. Note that the intensity and load are given in bit values; not actual values. Each complete transition from a maximum to a minimum in Figure 15 corresponds

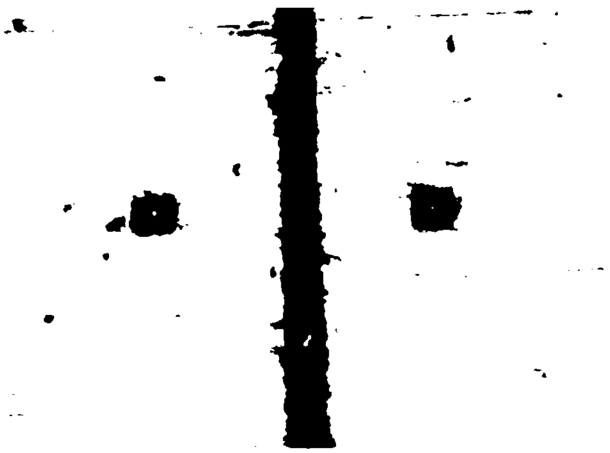

Figure 14: Indentations across the end of a long ISDG; the indentations are 200 micrometers apart.

to a displacement of approximately 1/2 micrometer, a strain of approximately 20 microstrain. So, in this configuration, the ISDG has reasonable resolution without the need for a sophisticated fringe scanning system. The minimum configuration would be a small (1 milliwatt) He-Ne laser, two photoresistors to sense the fringe intensity, and a two-pen X-Y plotter.

The results of an evaluation test are shown in Figure 16 where the strain computed from each fringe pattern separately is compared with that from a foil gage. The fringe motion due to relative displacement is so much greater than that due to rigid-body motion that the two patterns give essentially the same result. Note that these are actual data points; not averaged values, and the data points correspond to one complete fringe shift; not from a maximum to a minimum. The agreement is excellent over a range of about 1000 microstrain.

Use of a long ISDG at high temperatures requires further development in two areas: gage material and adhesive. The laser and the photosensors are quite straightforward; one would use an argon laser with more power and a shorter wavelength and a corresponding high quality interference filter. Ordinary photomultiplier tubes are more sensitive at the shorter wavelengths anyhow.

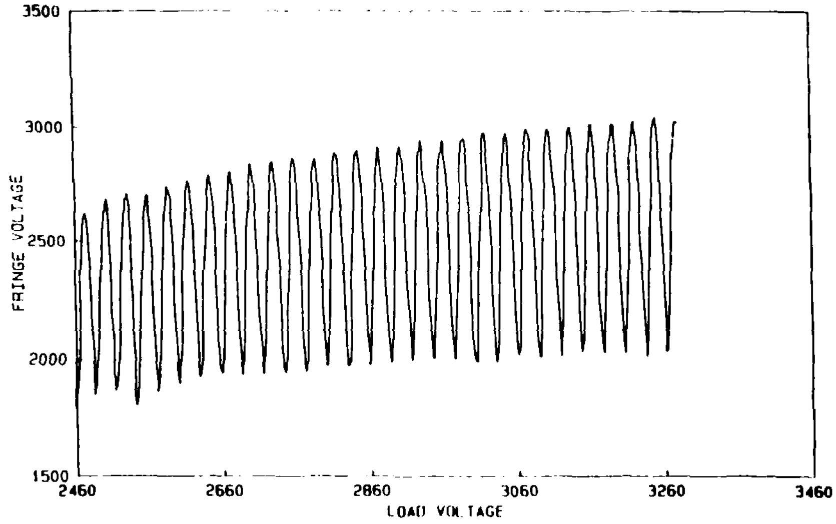

Figure 15: Fringe intensity versus load for a long ISDG.

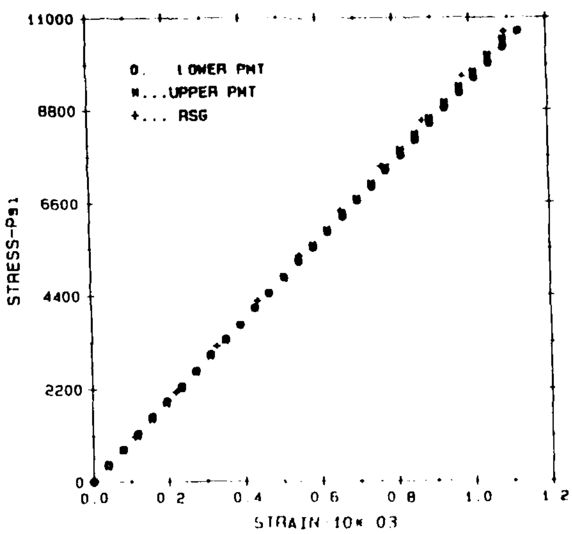

Figure 16: Strain from the long ISDG compared with RSG strain. The strain as measured by each fringe pattern is presented separately.

The gage material obviously needs to remain reflective at temperature. Platinum - 10 percent rhodium is a good candidate because it retains its reflectivity up to at least 1100C. Indentations have been etched in silicon single crystals by colleagues at the Applied Physics Laboratory. These produce beautiful fringe patterns and offer the potential of use at very high temperatures.

Perhaps an even more difficult problem for high temperature usage is finding a suitable adhesive that will absorb the differences in thermal expansion between the test piece and the gage material. AREMCO 517 ceramic adhesive from AREMCO Products, Inc. is a ceramic adhesive that can meet the needs if prepared and applied carefully. Mechanical attachment of the ISDG strips to the specimen is also possible.

A long gage was made with platinum - 10 percent rhodium and AREMCO 517 adhesive and heated to 1100C in a resistance furnace. The gage maintained its integrity and the fringes were quite adequate when illuminated with a laser after the heating cycle. This by no means guarantees that the gage would function under applied load, but facilities for loading a specimen at that temperature were not available.

CONCLUDING REMARKS

The attachable interferometric gages offer some advantages over direct indentations into the specimen. They can be used on specimens that are not naturally reflective and can be produced from materials that are resistant to high temperature or corrosive environments. Three versions of attachable gages are described in this report, but other combinations of gage material and adhesives can be explored.

Earlier applications of the ISDG used direct indentations, and these have the advantage of being integral with the specimen surface. It is possible that the adhesively attached gages could have problems in low-cycle fatigue testing as foil resistance gages do. If that is the case, the best combination may be a very thin foil attached to the specimen with an indentation that pierces the foil and indents only a fraction of a micrometer into the specimen surface. The soft foil would extrude onto the sides of the indent that are in the specimen and provide a better bond between specimen and foil as well as protecting the specimen.

The ISDG is a laboratory technique that is not very difficult to use and offers the advantage of realtime strain/displacement measurement over a very short gage length. It has an adequate resolution, a large range, and can be configured in a rosette form [6]. The attachable gages described in this report can extend its applications to studies of opaque materials such as polymer-based composites and graphites. The short gage length make it particularly attractive for the study of interfacial effects in such materials.

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